NATIONAL ENERGY TECHNOLOGY LABORATORY

A Comparative Assessment of CO2 Sequestration through Enhanced Oil Recovery and Saline Aquifer Sequestration

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National Energy Technology Laboratory (NETL), U.S. DOE

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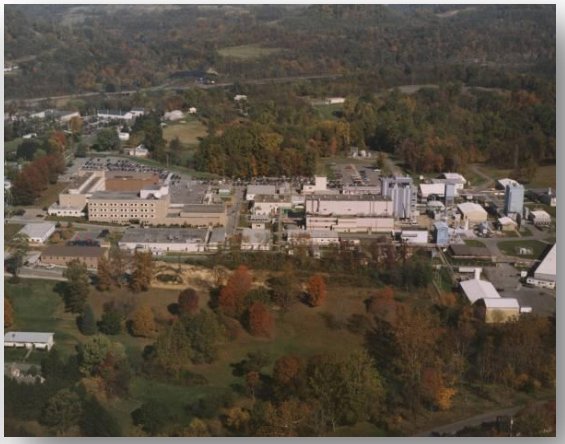


West Virginia

Alternative Carbon Management Strategies

- **Technology exists today to capture carbon from power plants and other industrial operations…what do you do with it?**

- **This study discusses two alternative carbon management strategies for storing captured carbon dioxide in geologic formations:**
  - Enhanced Oil Recovery using Carbon Dioxide (CO2-EOR)
  - Saline Aquifer Sequestration

- **Questions to be answered:**
  - What is the storage potential in the United States?
  - What is the life cycle GHG footprint of each option?
  - What are the trade-offs in deciding on a strategy?

What is CO_2 Enhanced Oil Recovery?

CO_2 enhanced oil recovery (EOR) is the injection of CO_2 into an underground oil-bearing formation for the purpose of increasing the amount of crude oil that can be produced

- **CO_2 stimulates oil production through**
  - Generation of CO_2/oil miscibility
  - Swelling of crude oil
  - Lowering of oil viscosity
- **CO_2 is stored through volumetric and solubility trapping**
  - Products include crude oil, natural gas, natural gas liquids
- **CO_2 EOR enables recovery of an extra 5-15% of original oil in place (OOIP)**
  - Primary and secondary recovery produce 20-40% of OOIP

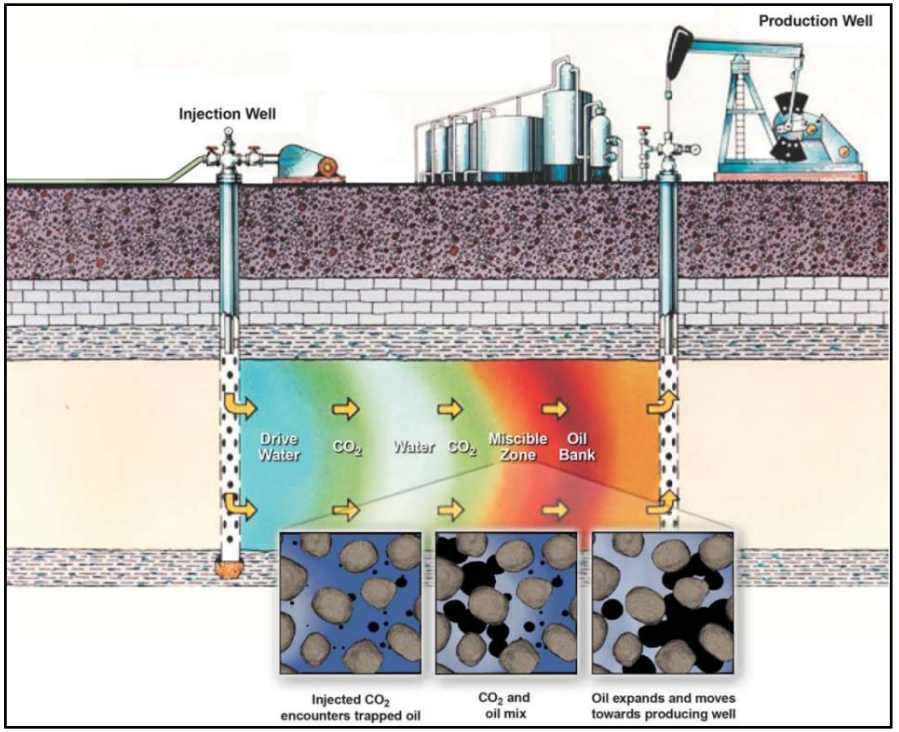
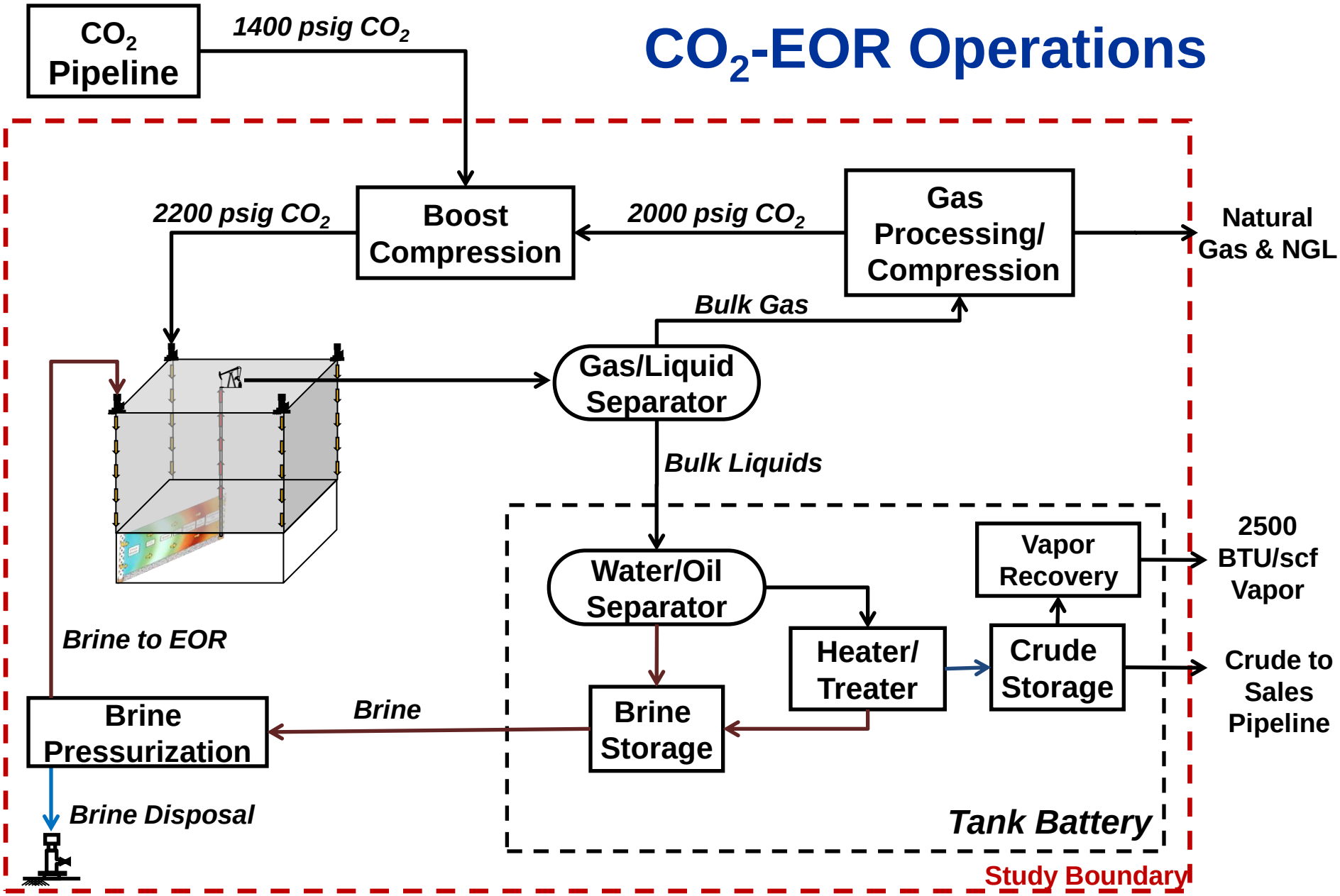


Image Source: U.S. Department of Energy. Carbon Dioxide Enhanced Oil Recovery *Untapped Domestic Energy Supply and Long Term Carbon Storage Solution (September, 2009). Accessed January 22, 2010 from:* http://www.netl.doe.gov/technologies/oil-gas/publications/EP/small_CO2_EOR_primer.pdf

CO_2-EOR Operations



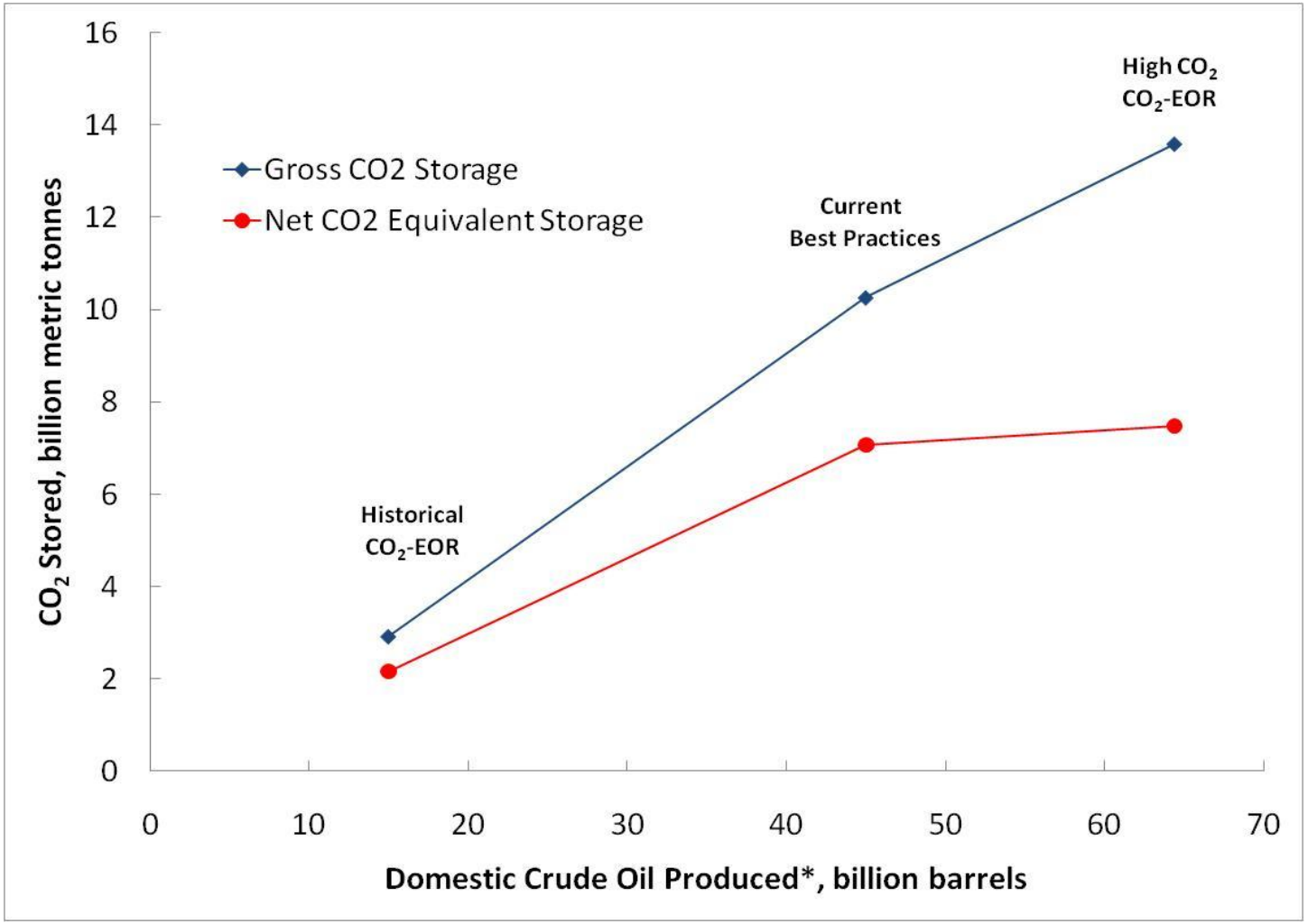
[1] National Energy Technology Laboratory. "Storing CO2 with Enhanced Oil Recovery." Report No. DOE/NETL-402/1312/02-07-08. NETL Contact: Lisa Phares. February 7, 2008. Accessed online 1/16/2009 from: http://www.netl.doe.gov/energy-analyses/pubs/Storing%20CO2%20w%20EOR_FINAL.pdf

[2] Lyons, William C. Standard Handbook of Petroleum & Natural Gas Engineering: Volume 2. Copyright 1996, Gulf Professional Publishing, Butterworth-Heinemann, Houston, Texas.

CO_2-EOR Scenario Definition

- **"Historical" CO_2-EOR**
  - 0.4 HCPV CO_2 is injected with water (WAG) into depleted oil reservoir
  - 1 HCPV slug of water recover a portion of injected CO_2
- **"Best Practices" CO_2-EOR**
  - 1.0 HCPV CO_2 WAG injection
  - No CO_2 recovered at end of flood
- **High CO_2 Injection CO_2-EOR increase oil production and CO_2 sequestration**
  - 1.5 HCPV CO_2 WAG injection
  - No CO_2 recovered at end of flood

Estimate of Domestic Oil Production and CO_2 Storage Potential



*Economically recoverable resource based on $70/bbl, $45/mt CO2, 15% project IRR (before tax); reported values are scaled to estimate total domestic production based on an estimated 75% coverage by ARI Big Oil Fields Database

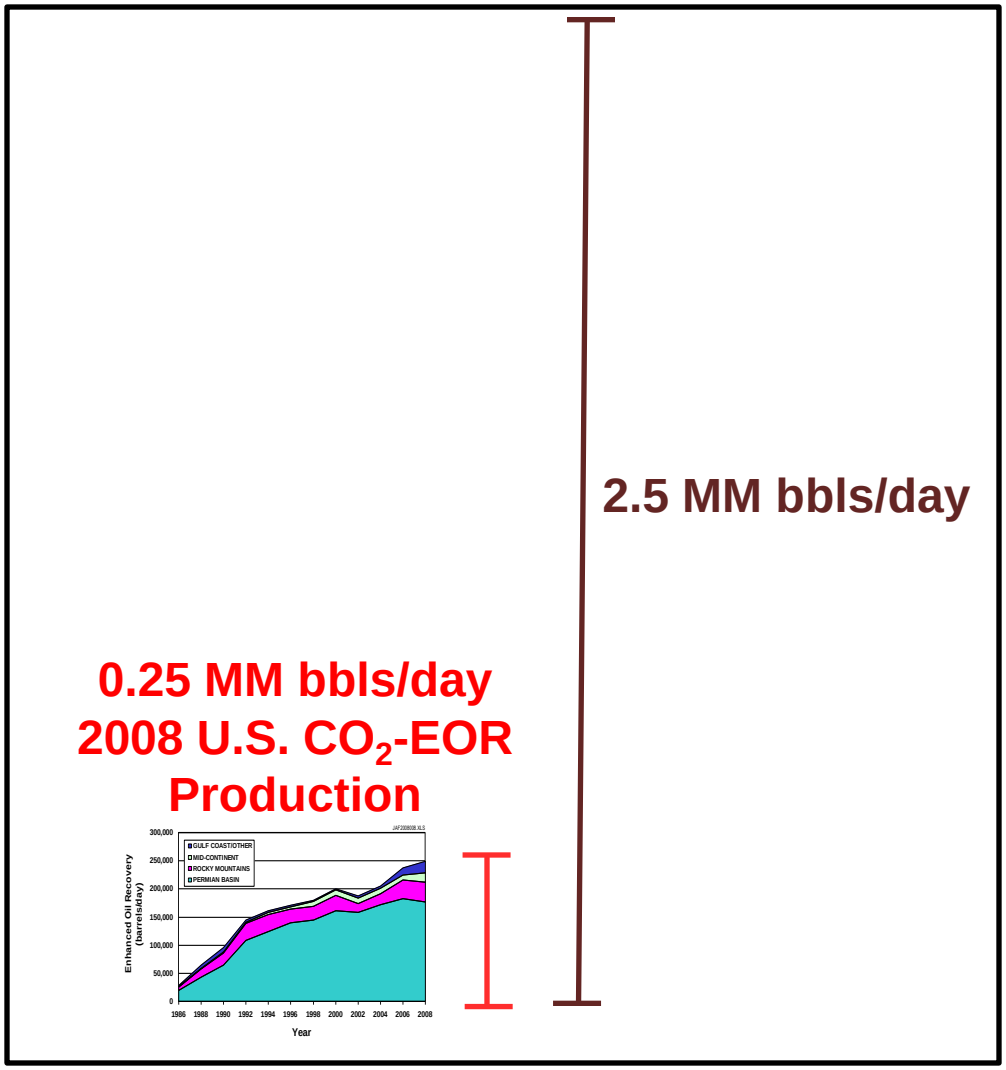
Adapted from:: National Energy Technology Laboratory. "Storing CO2 with Enhanced Oil Recovery." Report No. DOE/NETL-402/1312/02-07-08. NETL Contact: Lisa Phares. February 7, 2008. Accessed online 1/16/2009 from: http://www.netl.doe.gov/energy-analyses/pubs/Storing%20CO2%20w%20EOR_FINAL.pdf

National Energy Technology Laboratory. "An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO2-Enhanced Oil Recovery in the Permian Basin" Accessed online 10/28/2010 from: http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=333

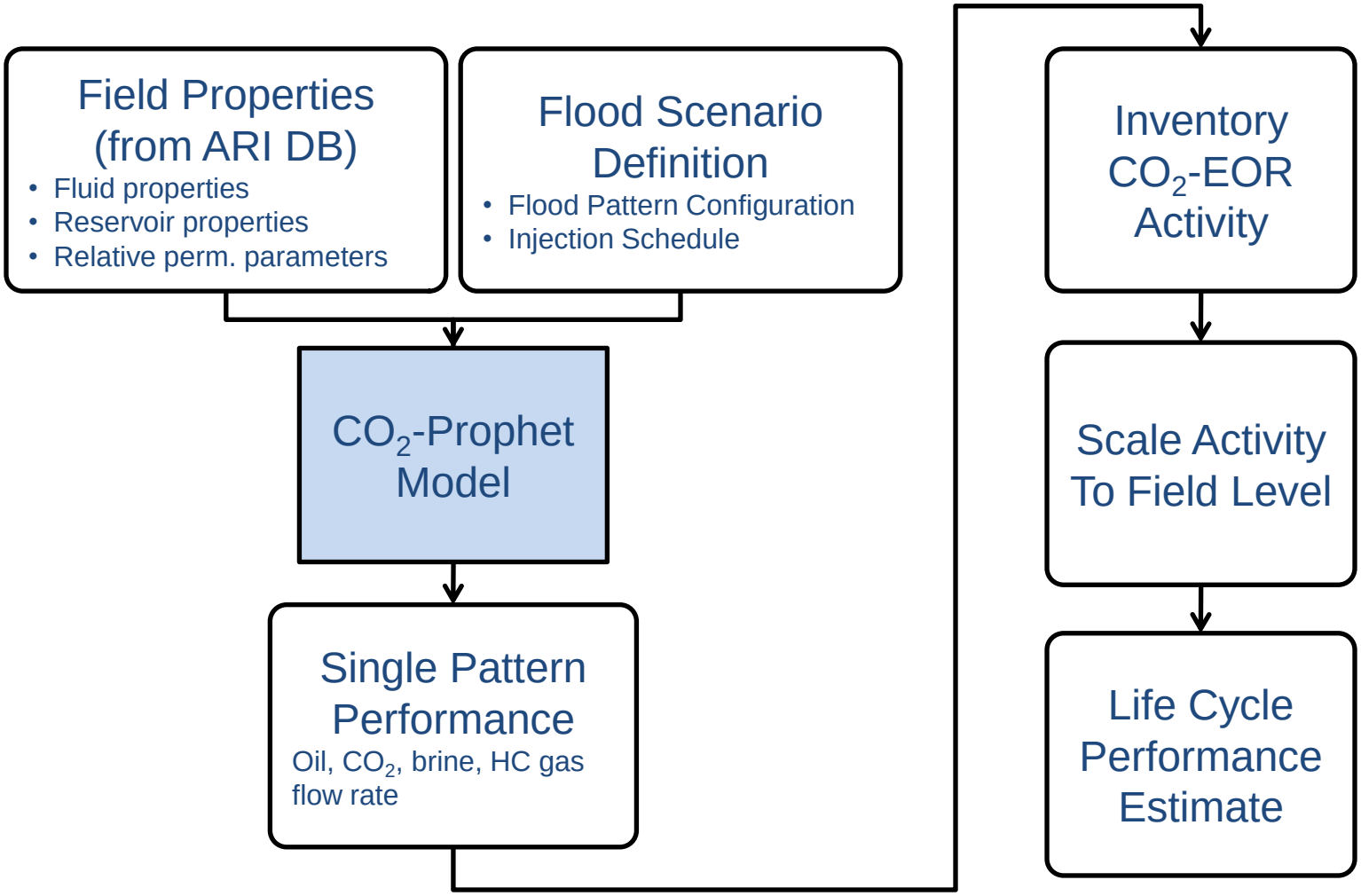
CO_2-EOR Production Potential in the U.S.

If produced over 50 years, 45 billion barrels is:

- 2.5 MM bbls/day
- 10X EOR production in 2008
- about 1/3 of 2009 domestic production



Life Cycle Inventory Modeling Approach: CO_2-EOR

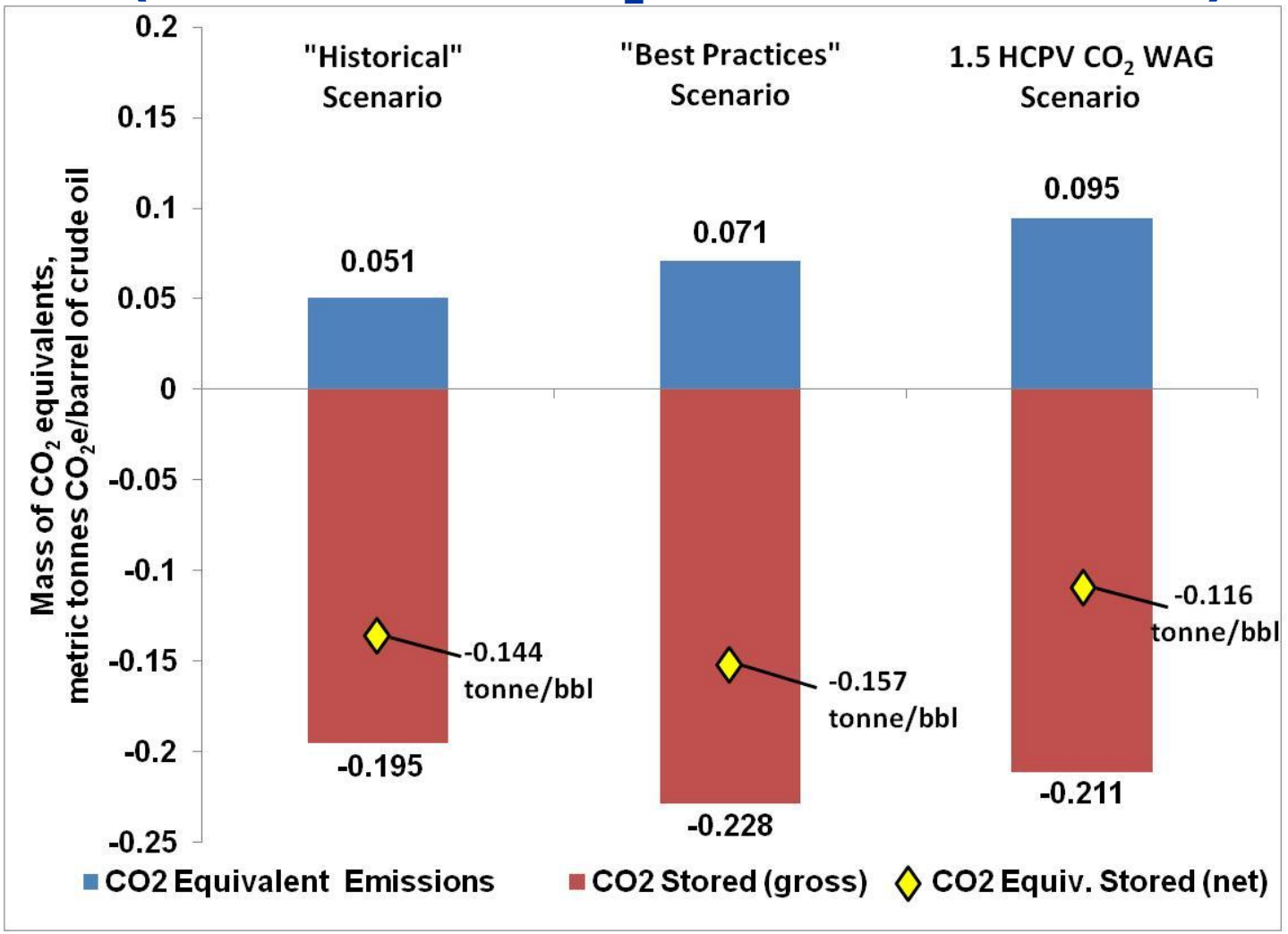


Life Cycle Inventory Modeling Approach: CO_2-EOR

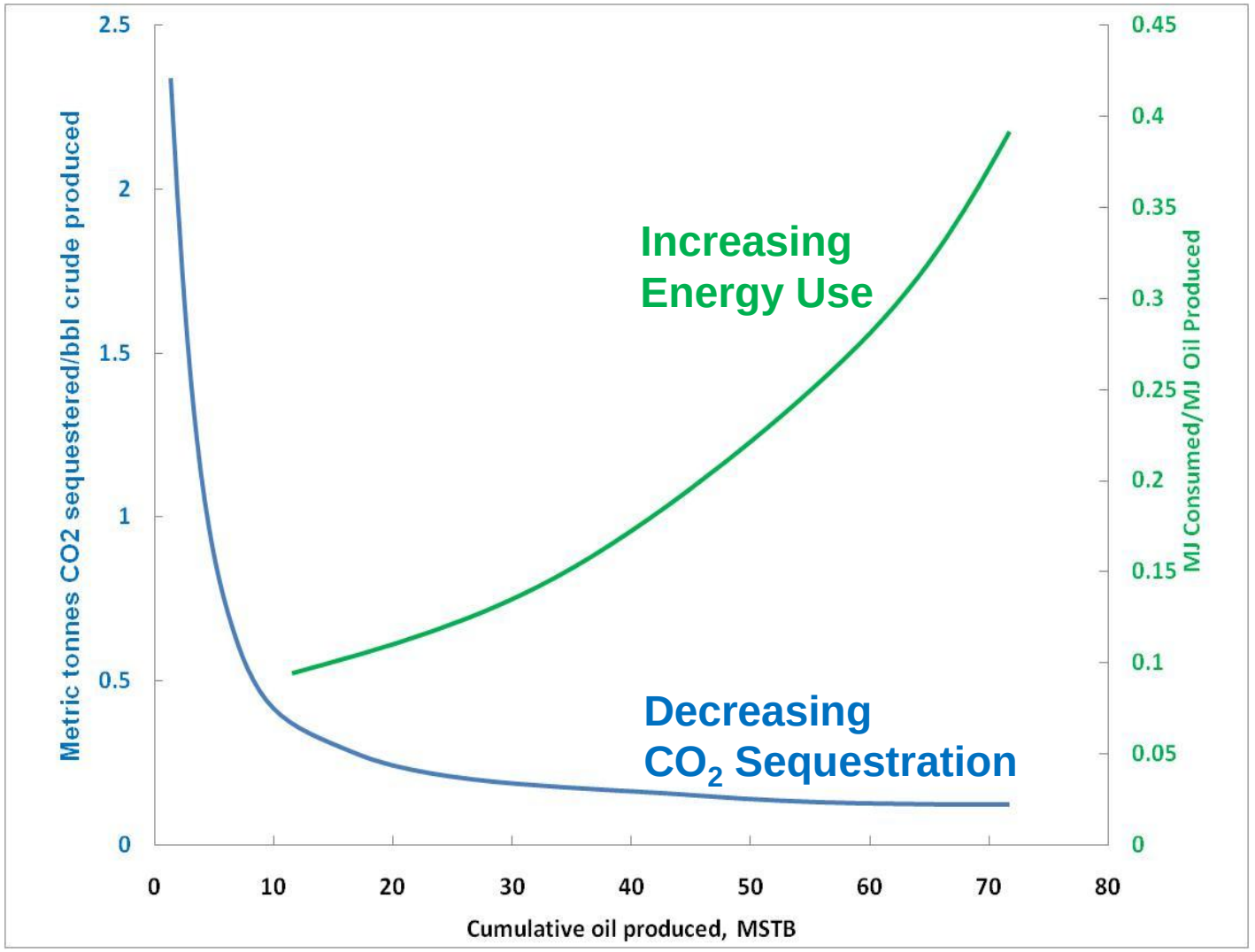
- **Includes Site Operation and Construction**
  - Site evaluation and characterization
  - Construction
  - Operation
  - Site Closure
  - Monitoring, Verification, and Accounting (MVA)

- **Life Cycle Inventory Data Reported**
  - Greenhouse gases (CO_2, CH_4, N_2O, SF_6)
    - Reported as CO_2 Equivalents, using 100-year, 2007 IPCC values
  - Criteria Air Pollutants (CO, SOX, NOX, PM)
  - Toxic Materials (Hg, Pb)
  - Land Use
  - Water use

CO_2-EOR GHG Performance
(metric tonnes CO_2e / barrel of crude oil)



Marginal Performance
"Best Practices" Flooding Scenario



Life Cycle Inventory GHG Results: CO_2 Enhanced Oil Recovery

CO_2-EOR Operational Scenario	Historical	Current Best Practices	1.5 HCPV CO_2 WAG [a]
CO_2 Injection Duration (single pattern, years)	7	**25**	36
Volume of CO_2 Injected as a Percent of the Total Pore Volume in the Target Formation [b]	0.4	**1.0**	1.5
Oil Recovery as a Percent of Original Oil in Place (OOIP)	12%	**17%**	21%
Percent of Injected CO_2 Recycled [c]	60%	**71%**	78%
Gross CO_2 Stored per Barrel of Oil Produced (kg CO_2/bbl oil) [c]	195	**228**	211
GHG Emissions per Barrel of Oil produced (kg CO_2e/bbl oil) [c]	51	**71**	95
Net CO_2 Stored per Barrel of Oil Produced (kg CO_2/bbl oil) [c]	144	**157**	116

a Assumes (1) improved technologies that enable more efficient contact between CO_2 and residual oil and (2) policy incentives for sequestering CO_2.

b Hydrocarbon pore volume (HCPV) is the pore volume in a reservoir initially filled with oil, and is often used to describe in-formation fluid volumes and discuss normalized performance between reservoirs. HCPV is calculated as $\sum A*h*\varphi*(1-Swi)$ where A = surface areas (40 acres), h = pay thickness (76 ft.), φ = porosity (0.11), and Swi = initial oil saturation as fraction (0.8).

c Values are average over the duration of the flood.

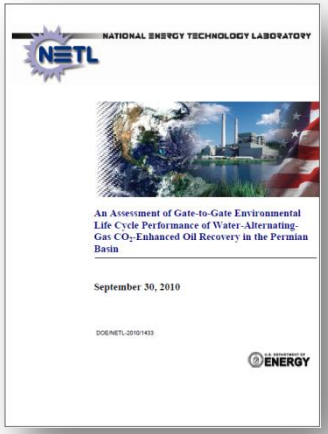
Results derived from single injection will modeling of a 40 acre 5-spot tapered WAG injection in a typical formation in the Permian basin, using the PROPHET model.

Key Findings: CO_2-EOR

- **Compared to primary and secondary recovery, CO_2 EOR requires a large amount of energy per barrel of crude oil produced**
- **"Best practices" CO_2-EOR performance*:**
  - gross sequestration benefit: 228 kg CO_2/bbl oil produced
  - operational emissions: 71 kg CO_2e/bbl oil produced
  - Energy consumption: 0.2 MJ per MJ oil produced
- **Marginal analysis shows diminishing performance per bbl as flood progresses**

Want more details?

NETL, 2010. *An Assessment of Gate-to-Gate Environmental Life Cycle Performance of Water-Alternating-Gas CO2-Enhanced Oil Recovery in the Permian Basin*. DOE/NETL 2010-1433
www.netl.doe.gov/energy-analyses Publication ID: 333



* Based on streamtube modeling of Permian Basin-type reservoir operated under "best practices" scenario miscible flood with 1 HCPV CO_2 water-alternating-gas injection and estimated inventory of surface operations; Flood details: water saturation: 0.31; porosity 0.11; pay thickness: 76 feet

What is Carbon Capture and Sequestration?

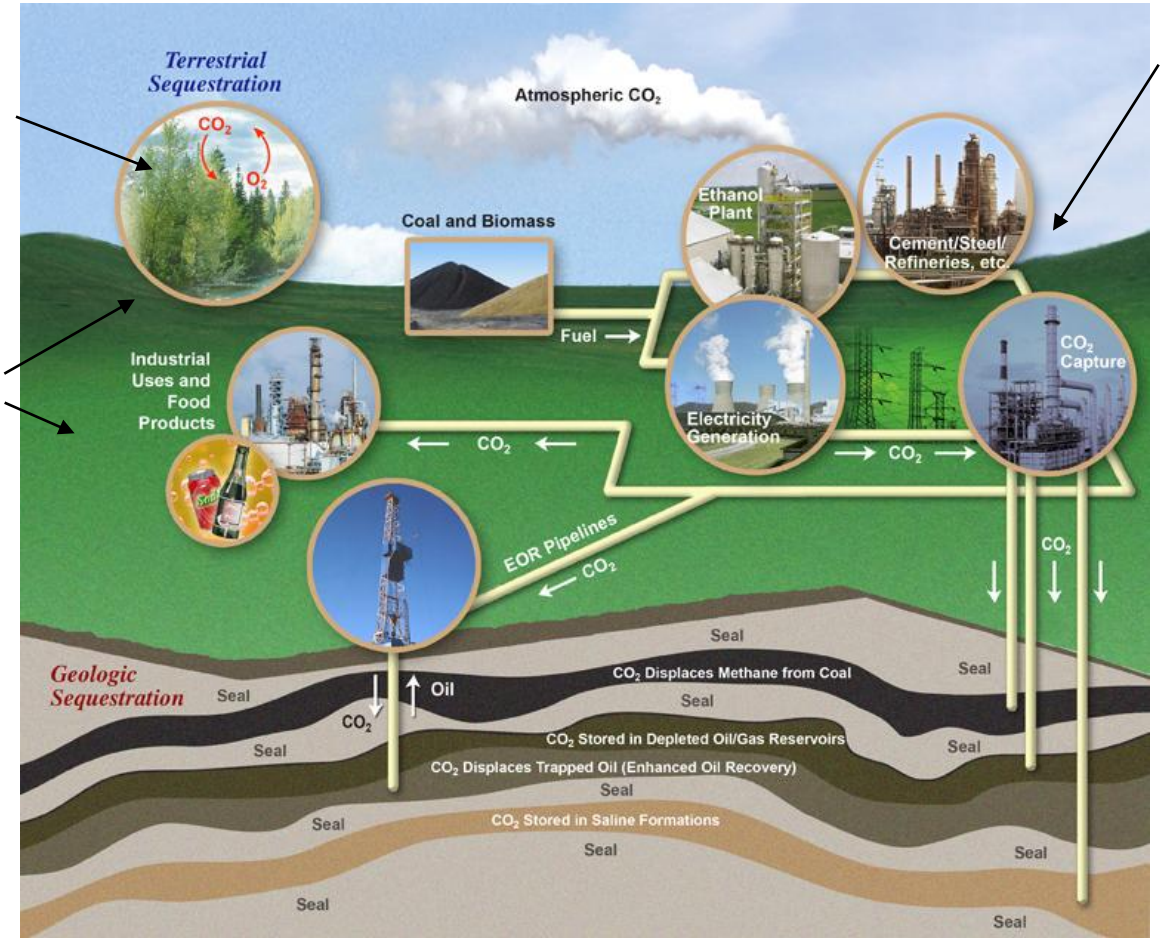
Capture and storage of CO_2 and other greenhouse gases that would otherwise be emitted to the atmosphere

Terrestrial Capture

CO_2 absorbed from air

Terrestrial Storage

Trees, grasses, soils



Point Source Capture

- *Power Plants*
- *Ethanol Plants*
- *Cement*
- *Steel*
- *Refineries*
- *Natural Gas Processing*

Geologic Storage

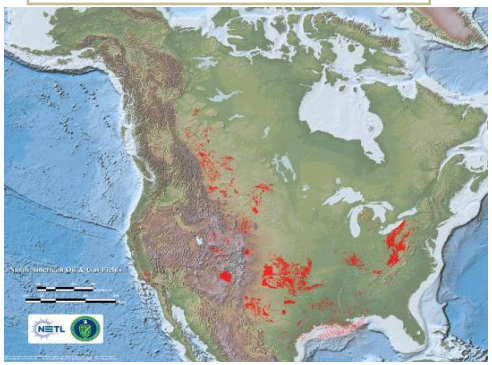
- *Saline formations*
- *Depleted oil/gas*
- *Unmineable coal*
- *Other: basalts, shales*

National Atlas Highlights

Hundreds of Years of Storage Potential

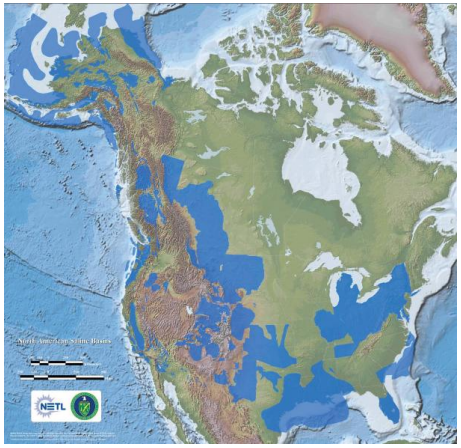
U.S. Emissions ~ 6 GT CO_2/yr all sources

2008 Conservative Resource Assessment



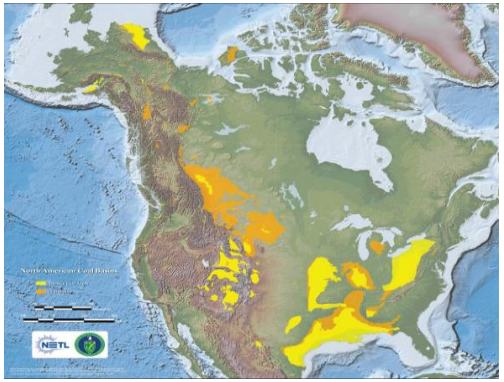
Oil and Gas Fields

*138 GT CO_2 Storage Resource**



Saline Formations

*3,300–12,600 GT CO_2 Storage Resource**



Unmineable Coal Seams

*157-178 GT CO_2 Storage Resource**

Carbon Sequestration Atlas of the United States and Canada (Atlas III)

Release date: November 2010

Featuring updates:

- **DOE's Carbon Sequestration Program**
- **DOE's International Collaborations**
- **DOE's National Risk Assessment Partnership (NRAP)**
- **Regional Carbon Sequestration Partnership (RCSP) Activities**
- **Refined CO_2 source estimates and CO_2 storage potential across the RCSP regions**
- **Worldwide CCS projects, CCS regulatory issues**
- **NATCARB's improved databases and GIS system**

**2008 Carbon Sequestration Atlas of the United States and Canada.*

Available for download at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasII/atlasII.pdf

Large Geological Storage Projects Underway

Each Stores > 1 Million Tonnes CO_2/yr

Sleipner Project- Norway

- CO_2 removed from natural gas produced on production platform in North Sea
- Injection into saline reservoir under sea
- Started 1996

Weyburn – Saskatchewan

- EOR project with 50 wells
- Uses CO_2 from coal gasification plant
- Started 2000

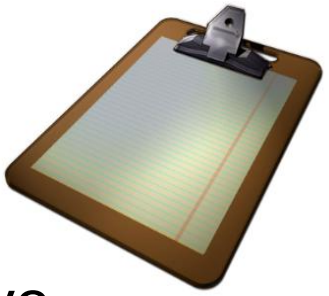
In Salah Gas Plant - Algeria

- Injection into saline formation downdip of gas reservoir
- Started 2004

Photos from Staoil Website

Life Cycle Inventory Modeling Approach: Saline Aquifer Operations and Monitoring

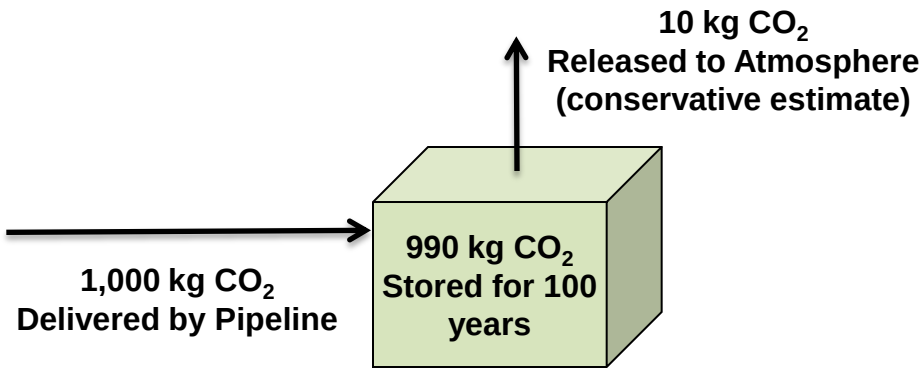
- **Operations are minimal**
  - No pumps or other energy-consuming facilities at injection site
  - No energy consumption at the injection site
  - Only infrastructure at the site: pipeline and injection well
- **Leakage Rate and Monitoring**
  - Saline sequestration is not well-established infrastructure; leakage rate is uncertain
  - 1%/100 year leakage rate is likely conservative (overestimate)
  - Leakage rate over 1% would not be a candidate for CO_2 sequestration.



Life Cycle Inventory GHG Results: Saline Aquifer Sequestration

- **10 kg CO_2e/tonne CO_2 Delivered**
- **10.1 kg CO_2e/tonne CO_2 Sequestered**

Emissions from site characterization, MVA, and site closure are insignificant compared to the conservative estimate of 1% leakage over 100 years of storage.



CO_2-EOR vs. Saline Aquifer Sequestration

What are the trade-offs?

Characteristic	CO_2-EOR [a]	Saline Aquifer
U.S CO_2 Storage Potential, net	~ 7 B tonne	3,300 – 12,600 B tonne
Domestic Oil Production Potential	45 Bbbls	0 Bbbls
Barrels of Domestic Crude Oil per Tonne CO_2 Delivered	4.4	0
GHG Footprint, net *(UNALLOCATED)* (kg CO_2e/tonne CO_2 sequestered)	452	10.1
GHG Footprint *(UNALLOCATED)* (kg CO_2e/tonne CO_2 delivered)	311	10.0

a Best Practices Scenario

CO_2-EOR Allocation Challenge:
Who gets credit for storing the CO_2?

- **The Energy Conversion Facility that captured the CO_2?**
- **The CO_2-EOR operation that stored the CO_2?**

- **Allocation Options to Consider:**
  - Physical Property of the Co-products
    - Energy, Mass, Volume
  - Economic Value of the Co-products
  - Displacement Method
    - Displace the Average or Marginal Production of Crude Oil from the CO_2-EOR operation
    - Displace the CO_2 Captured by the Energy Conversion Facility by Naturally Sourced CO_2

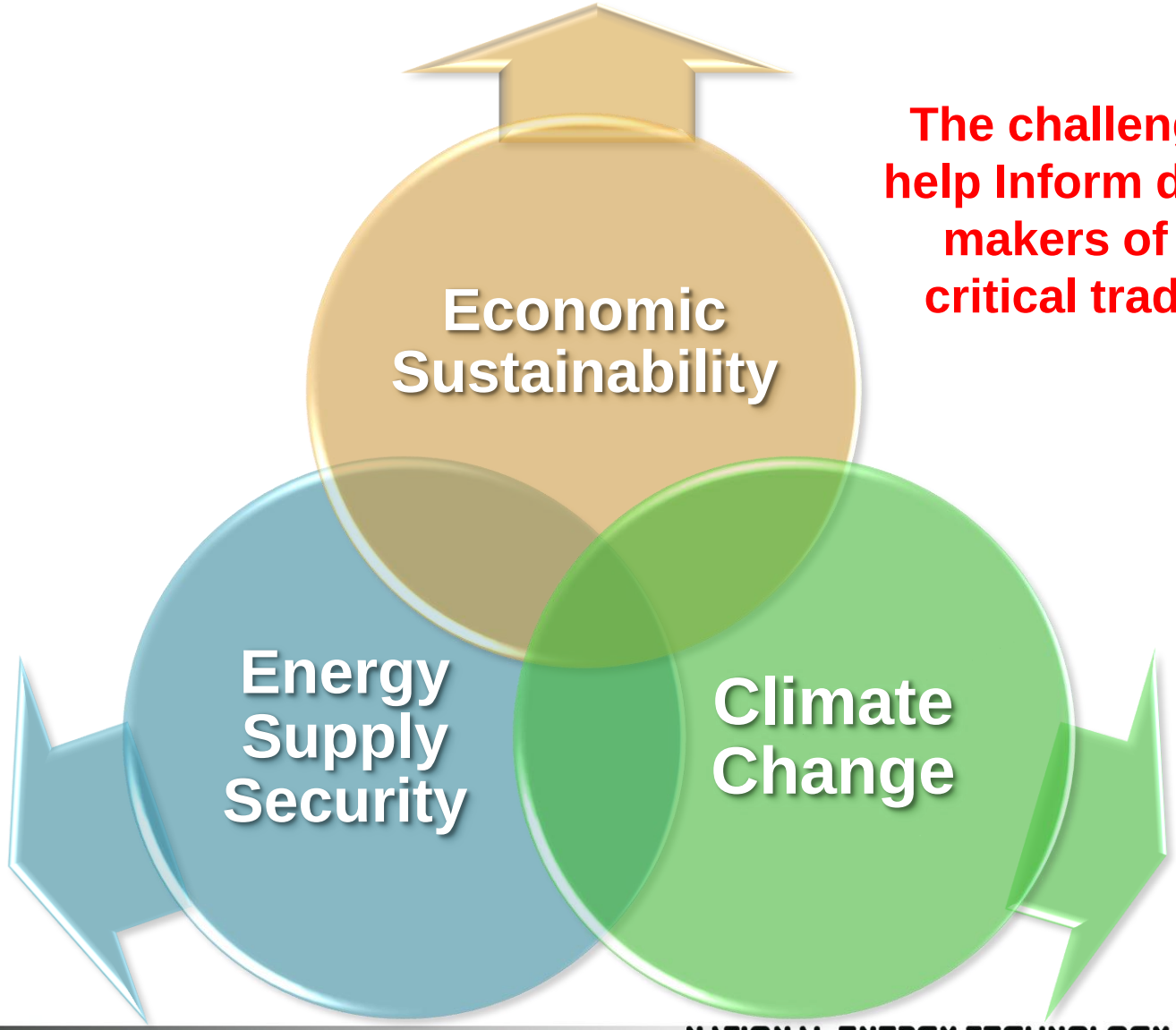
Hypothetical Example:
Advanced Coal-fired Power Plant with 90% Carbon Capture

Study Properties:

- **Net Power Output (Busbar):** **556 MWh**
- **Cradle-to-Busbar GHG Emissions:** **213 kg CO_2e/MWh**
- **CO_2 Captured:** **1,060 kg CO_2/MWh**
- **CO_2-EOR, Crude Oil Production:** **4.7 bbls/MWh**
- **CO_2-EOR GHG Emissions:** **330 kg CO_2e/MWh**

Allocation Method		Electricity (kg CO_2e/MWh)	Crude Oil (kg CO_2e/bbl)
Unallocated Results	[Total: 543 kg CO_2e/MWh]	213	71
Energy, HHV		61	103
Economic Value	[$0.16/kWh, $85/bbl]	157	83
Displacement: Crude Oil, US Average	[36 kg CO_2e/bbl]	375	n/a
Displacement: Crude Oil, Marginal, Heavy	[100 kg CO_2e/bbl]	76	n/a
Displacement: Crude Oil, Marginal, Light	[20 kg CO_2e/bbl]	450	n/a
Displacement: Natural Sourced CO_2	[0.01 kg CO_2e/kg CO_2]	202	n/a

Alternative Carbon Management Strategies have Inherent Trade-offs Between National Priorities!



The challenge is to help Inform decision-makers of these critical trade-offs.

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